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SOIL REDISTRIBUTION AND PEDOLOGIC TRANSFORMATIONS IN COASTAL PLAIN CROPLANDS

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ABSTRACT

In agricultural basins of the southeastern coastal plain there are typically large disparities between upland soil erosion and sediment delivered to streams. This suggests that colluvial storage and redistribution of eroded soil within croplands is occurring, and/or that processes other than fluvial erosion are at work. This study used soil morphology and stratigraphy as an indicator of erosion and deposition processes in a watershed at Littlefield, North Carolina. Soil stratigraphy and morphology reflect the ways in which mass fluxes associated with cultivation transform the local soils. Fluvial, aeolian and tillage processes were all found to be active in the redistribution of soil. The soil transformations are of five general types. First, erosion and compaction in the cultivated area as a whole result in the thinning of Arenic and Grossarenic Paleudults and Paleaquults to form Arenic, Typic and Aquic Paleudults and Paleaquults. Second, redistribution of surficial material within the fields results in transitions between Arenic and Typic or Aquic subgroups as loamy sand A and E horizons are truncated or accreted. Third, aeolian deposition at forested field boundaries leads to the formation of compound soils with podzolized features. Fourth, sandy rill fan deposits at slope bases create cumulic soils distinct from the loamy sands of the source area or the darker, finer terrace soils buried by the fan deposits. Finally, tillage and fluvial deposition in upland depressions results in the gradual burial of Rains (poorly drained Typic Paleaquults) soils. Results confirm the importance of upland sediment storage and redistribution, and the role of tillage and aeolian processes as well as fluvial processes in the region. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS soil erosion; deposition; soil stratigraphy; pedologic transformations; colluvium

INTRODUCTION

It has been increasingly recognized in recent years that despite low slopes, a prevalence of sandy permeable soils, dense natural vegetation, and the relative scarcity of visible erosion indicators, the southeastern coastal plain has undergone historic soil erosion at rates of significance both to geomorphology and environmental management (Dendy, 1981; Cooper *et al*., 1987; Soller, 1988; Lowrance *et al*., 1988; Phillips *et al*., 1993; Phillips, 1997; Slattery *et al*., 1997). Much of the soil loss is clearly due to fluvial processes, as evidence of recent and historical sedimentation linked to upland erosion abounds.

However, there are typically large discrepancies between measurements or estimates of soil loss, erosion or truncation on the uplands, and fluvial sediment yield or alluvial sedimentation. Measurements or estimates of erosion rates on cropland typically range from 5 to more than 30 t ha^{-1} a^{-1} (Beasley, 1979; Dendy, 1981; Sheridan *et al*., 1982; Lowrance *et al*., 1986, 1988; Cooper *et al*., 1987; Phillips, 1993, 1997; Phillips *et al*., 1993; Slattery *et al*., 1997), while sediment yields of coastal plain streams are, at least an order of magnitude lower (Dole and Stabler, 1909; Kennedy, 1964; USDA, 1979; Simmons, 1988; Hubbard *et al*., 1990; Kim, 1990). The disparity between sediment eroded from

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hillslopes and fluvial sediment yields is well known and occurs in a variey of environments, but is often particularly evident in the coastal plain. Phillips (1995) constructed a rudimentary sediment budget for the coastal plain rivers of North Carolina for the time since European expansion (about 1700). Estimated regional erosion rates are on the order of 9–10 t ha^{-1} a^{-1}, while sediment yield to estuaries is low (0·03 to 0·06 t ha^{-1} a^{-1}). The estimated alluvial deposition rates amount to about 1·2 t ha^{-1} of upland. Thus, less than 13 per cent of the apparent soil loss is delivered to estuaries or stored as alluvium, imploying that 80 to 90 per cent is typically accounted for either as colluvial storage, or is removed by processes other than fluvial erosion. The general results are consistent with studies at more restricted scales. Cooper *et al.* (1987) examined a field in the Chowan River basin of eastern North Carolina and found that about 80 per cent of the sediment lost from the site was deposited as colluvium at the field edges or in minor depressions. Sheridan *et al.* (1982) found in a small watershed in the Georgia Coastal Plain that 85 to 99 per cent of the eroded soil was stored as colluvium under contemporary conditions. Phillip (1993) found a large disparity between post-colonial upland erosion rates and stream sediment yields ($\geqslant$9·5 and $<$0·02 t ha^{-1} a^{-1}, respectively) in the lower Neuse River basin, North Carolina.

The disparity between upland erosion and sediment delivered to streams suggests that there is significant colluvial storage and/or soil movement due to factors other than water erosion, such as aeolian processes and tillage. However, colluvial storage has generally been measured or estimated as a residual. Coastal plain colluvium has no stone lines or other readily observed features which sometimes aid recognition of colluvial soils in other environments. We are also aware of few studies of aeolian erosion in humid temperate environments in general (other than in coastal beach and dune settings), and none in the southeastern USA. There is, therefore, a need for a more detailed assessment of colluvial storage and upland soil redistribution in the coastal plain, and for determining the pedologic signatures of these phenomena.

There is evidence that agriculture-induced mass redistributions can result in significant pedologic changes in relatively short times. These changes may affect gross soil profile morphology and the taxonomic classification of the soils, in addition to more subtle changes in soil physical and chemical properties. King *et al.* (1983) not only demonstrated relationships between topographic elements, soil movement processes, soil thickness, and other soil properties, but also how these relationships could be incorporated into soil mappings in Canadian prairie landscapes. In north central USA, Mokma *et al.* (1996) showed that the morphological effects of erosion are often significant enough to change the classification of soils at all levels of soil taxonomy. Kreznor *et al.* (1989) compared cultivated and uncultivated pedons in northwest Illinois, and found that morphological changes associated with cultivation were sufficient to cause a transition from Mollisols to Alfisols. Erosion of adjacent agricultural land is apparently responsible for the Chowan series, a Thapto-Histic Fluvaquent mapped in the lowermost coastal plain of North Carolina (Phillips, 1992). This soil is an alluvial organic muck buried by 40 to 100 cm of mineral soil derived from nearby uplands. In east Shropshire, England, only six years of erosion on loamy sands was sufficient to increase sand percentages by about 7 per cent, and decrease silt and clay percentages by about 8 and 1·3 per cent, respectively (Fullen and Brandsma, 1995). This rate of change would be sufficient in many cases to result in changes in textural class.

The objectives of this paper are to (1) identify soil transformations associated with erosion, deposition and soil redistribution by water, wind and tillage, and (2) determine the pedologic signatures of particular redistribution processes. By achieving these objectives, soil stratigraphic information can be used to link landscape evidence of decadal and longer-scale sediment fluxes to contemporary process measurements.

A comprehensive review of the effects of geomorphic processes and agriculture on soil properties is beyond the scope of this paper. We will focus on soil morphology as expressed primarily in the type, thickness and sequence of soil horizons. The presence or absence of diagnostic horizons, and their thickness, may be important in classifying soils at all levels of soil taxonomy. There are five general direct effects of soil removal or additions on soil morphology, all of which would be expected to have a number of indirect influences.

(1) *Truncation*: constitutes soil thinning and surface lowering, but not of a magnitude sufficient to completely remove surficial horizons.
(2) *Horizon destruction*: soil loss sufficient to result in the complete removal of one or more surficial horizons.
(3) *Upbuilding*: the accretion of surficial material to create overthickened surface horizons and a cumulic or cumulative soil. In agricultural areas this is often manifested as relatively thin and regular additions of sediment that are subsequently incorporated into the plough layer.
(4) *Burial*: the rapid or deep burial of the pre-depositional soil profile, or the retardant upbuilding of Johnson and Watson-Stegner (1987). The US Natural Resources Conservation Service (formerly Soil Conservation Service) considers soils to be buried when at least 50cm of deposition has occurred. In this study an operational differentiation between upbuilding and burial may be based on whether accretion is thicker than the plough layer (based on the depth of the base of Ap horizons at the site, which is about 29cm). We will also consider soils to be buried when deposits are thick enough to allow secondary pedogenic features to form.
(5) *Secondary pedogenic features*: features resulting directly from erosion or deposition; for example Bw horizons produced in thick deposits over buried soils, or coarse lag surfaces produced by erosional winnowing.

STUDY AREA

The Littlefield site is named for the nearby crossroads community in Pitt County, North Carolina. This is the location of ongoing studies of contemporary fluvial and aeolian processes (see Acknowledgements). The 71ha study area (Figures 1 and 2) is situated on the Pleistocene Wicomico marine terrace of the coastal plain. Parent material is loamy to coarse-loamy unconsolidated coastal, marine and alluvial sediments. The climate is humid subtropical. A gently rolling to flat upland area of the site, about 36ha, is in mixed pine and hardwood forest, while the remainder has been in row crop agriculture for at least a century. Primary crops are tobacco and cotton at present, but corn and soybeans have also been cultivated there.

Maximum elevation is only 20m above mean sea level, and slopes are generally less than 2 per cent. Maximum relief is 8m. The main natural drainageway has been channelized to function as a drainage canal, and a network of field ditches is in place to lower water tables to increase surface trafficability and optimize plant moisture conditions. These ditches, roadway and a railroad track conveniently divide the site into fields, labelled A to E in Figure 1.

Soils are generally Paleudults and Paleaquults in the US soil taxonomic system (Soil Survey Division Staff, 1993). Some series mapped at the site are formally classified as Kandiudults, but Kleiss (1994) has shown that Ultisols on the lower coastal plain of North Carolina rarely meet the kandic criteria. Most of the soils have loamy sand A and E horizons overlying sandy clay loam argillic (Bt) horizons. Base saturation and pH are generally low. Valley-bottom soils are derived from alluvial terrace deposits, and are darker and finer than the slope and upland soils. The soils are described in much greater detail in the Results (see also the soil map in Figure 5).

METHODS

Topography of the study area was surveyed using a Topcon total station and prism. Soils were mapped at a scale of 1:6000, based on two soil pits, ditch-wall exposures, and numerous augerings and borings. Field-mapping procedures were generally similar to those described by McRae (1988). Visible erosion and deposition features were also mapped. Soil profile descriptions are according to standard US Department of Agriculture procedures (Soil Survey Division Staff, 1993).

Additional excavations and trenches were dug at sites of apparent erosion or deposition, and along field-edge ridges evident along the forest–field boundary. Depth to the top of the argillic (Bt) horizon

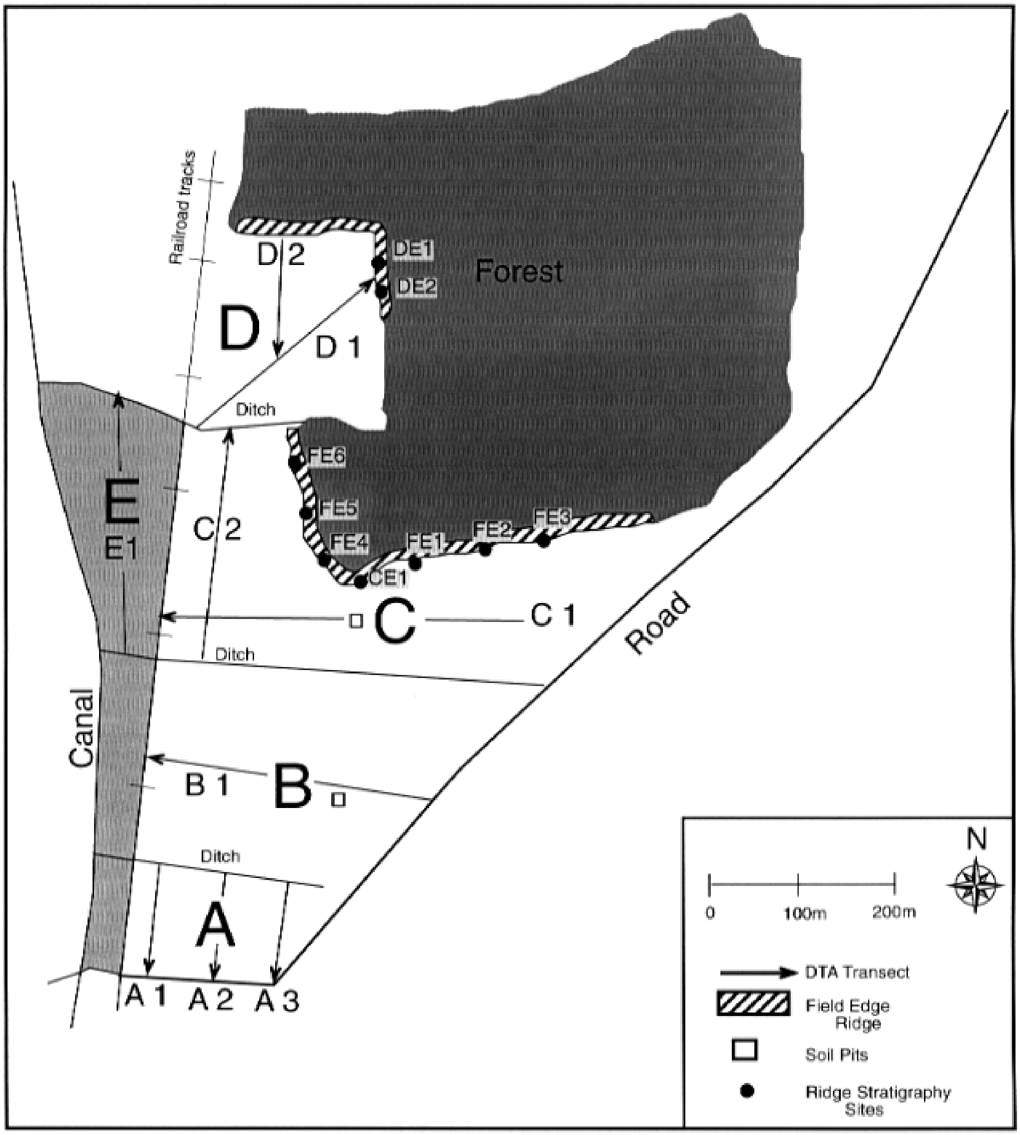

Figure 1. The study area in Littlefield, North Carolina, USA, showing individual fields and sample sites referred to in the text. The FE designations for ridge stratigraphy sites refer to field-edge ridges; sites CE1, DE1 and DE2 were added later. The family cemetery referred to in the text is immediately to the left (west) of the soil pit in field C

(DTA) was measured at 10m intervals along nine linear cross-field transects, so that spatial variability in surface horizon thickness could be observed and, if possible, related to topography and surface features. An additional 60DTA measurements were taken within the southern and western portions of the forested area within 200m of the cultivated land. While colour contrasts are often helpful in recognizing the Bt horizon, the transition from sandy loam or coarser to sandy clay loam or finer textures, and from granular to subangular blocky structures, makes the field identification of the argillic horizon straightforward. DTA measurements in the fields were made with soil probes, and are estimated to be accurate to within ± 1cm to a depth of 0·5m, and to within ± 3cm to a depth of 1·5m. The high water tables in much of the forest required the use of a dutch mud auger for many samples, with an estimated accuracy of ± 7cm to a depth of 1·5m.

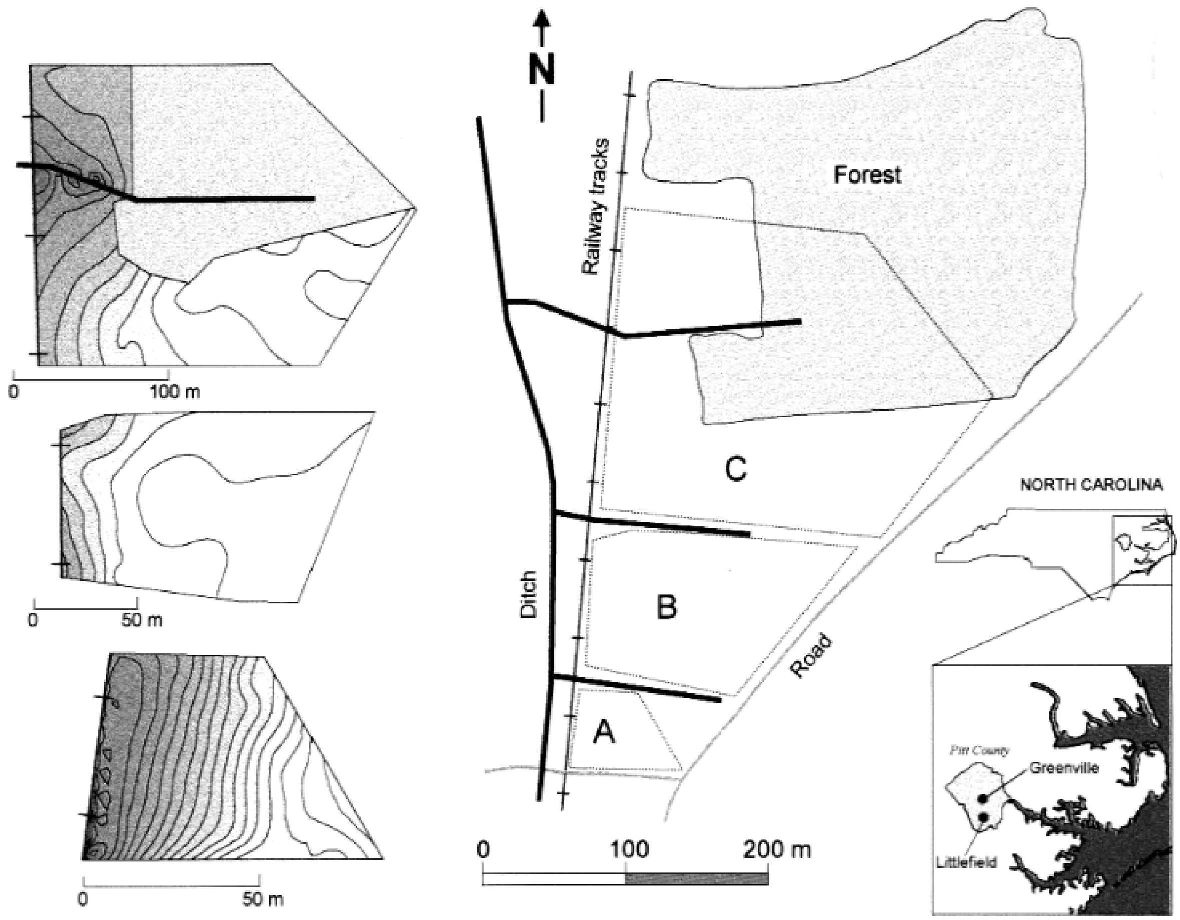

Figure 2. Topography of the individual fields and general location map. The contour interval is 0·15 m; the railroad tracks are the zero datum

A family cemetery exists within the cropped fields. As is often observed in the region, the permanently vegetated cemetery is obviously elevated or perched relative to the surrounding cropland. This suggests the possibility of using the cemetery as a datable surface to estimate surface lowering. In addition to topography, DTA measurements were taken in apparently undisturbed parts of the cemetery and the immediately adjacent fields for comparison. Six core samples each of both field and cemetery A horizons were taken for laboratory determination of bulk density. The cemetery was also examined for evidence of deposition due to tillage or aeolian processes.

RESULTS

Soils

The two soil pits (Table I) are generally representative of the soil morphology on much of the site (with the exception of the valley bottom), at least with respect to the subsurface morphology and the general character of the A and E horizons. The latter vary substantially in thickness and the presence of secondary pedogenic features, but are all siliceous loamy sands of similar colour and structure. The soils sampled in the pits are the Norfolk and Wagram series. These Kandiudults/Paleudults have loamy sand

Table I. Soil profile descriptions

Soil pit1: Field C, Norfolk Series
Ap – 0 to 12 cm; brown (10YR 4/3) loamy sand;. weak fine granular structure; very friable; many fine roots; common fine to coarse charcoal fragments; few uncoated sand grains; strongly acid; clear wavy boundary.
Ap2 – 12 to 30 cm; brown (10YR 4/3) loamy sand; weak fine granular structure; very friable; few fine roots; common fine to coarse charcoal fragments; many uncoated sand grains; strongly acid; clear smooth boundary.
E – 30 to 42 cm; very pale brown (10YR 7/4) loamy sand; weak medium granular structure; very friable; many fine to coarse charcoal fragments; few fine roots; strongly acid; gradual smooth boundary.
B + 1 – 42 to 86 cm; dark yellowish brown (10YR 4/6) sandy clay loam; many medium faint yellow (10YR 7/6) mottles; moderate coarse subangular blocky structure; firm slightly sticky and slightly plastic; thick, continuous clay films on ped faces and coating grains; common fine charcoal fragments; extremely acid; gradual diffuse boundary.
B + 2 – 86 to 125 cm; reddish yellow (7.5YR 6/8) sandy clay loam; many coarse distinct light grey (10YR 7/2) mottles; moderate coarse subangular blocky structure; firm, sticky and plastic; thin, discontinuous clay films on ped faces and coating grains; common fine charcoal fragments; very strongly acid; boundary not observed.
B + 3 – 125 to 200 cm; yellowish brown (10YR 5/6) sandy clay loam; many coarse distinct yellowish red (5YR 5/8) and grey (10YR 7/1) mottles; strong coarse subangular blocky structure; firm, sticky and plastic; thin, continuous clay films on ped faces and bridging grains; common fine to coarse charcoal fragments; extremely acid; clear wavy boundary.

Soil pit2: Field A, Wagram Series
Ap – 0 to 29 cm; brownish yellow (10YR 6/6) loamy sand; moderate medium granular structure; very friable; many fine to very coarse charcoal fragments; few uncoated grains; common fine to coarse roots; medium acid; clear smooth boundary.
E – 29 to 62 cm; very pale brown (10YR 7/4) loamy sand; weak medium granular structure; very friable; common fine to very coarse charcoal fragments; few fine roots; medium acid; clear broken boundary.
Bt1 – 62 to 110 cm; brownish yellow (10YR 6/8) sandy clay loam; few medium faint yellowish red (7.5YR 5/8) mottles; moderate coarse subangular blocky structure; firm; thin discontinuous clay films on ped faces and coating grains; few fine to coarse charcoal fragments; very strongly acid; gradual wavy boundary.
Bt2 – 110 to 136 cm; brownish yellow (10YR 6/8) sandy clay loam; common fine to coarse distinct strong brown (5YR 4/6) mottles; moderate coarse subangular blocky structure; firm, slightly sticky and slightly plastic; thin discontinuous clay films on ped faces and coating grains; common fine to medium charcoal fragments; very strongly acid; boundary not observed.
Bt3 – 136 to 165 cm; reddish yellow (7.5YR 6/8) sandy clay loam; many coarse prominent strong brown (5YR 5/8) and common pinkish grey (7.5YR 6/2) mottles; moderate coarse subangular blocky structure; firm; thin discontinuous day films on ped faces and coating grains; few fine to coarse charcoal fragments; very strongly acid; boundary not observed.
Btg – 165 to 200 cm; yellowish red (7.5YR 5/8) clay; common coarse prominent light grey (7.5YR 7/1) and coarse distinct red (2.5YR 4/8) mottles; strong coarse subangular blocky structure; very firm, slightly sticky and slightly plastic; thick continuous clay films on ped faces; common fine to medium charcoal fragments; very strongly acid.

Table II. Taxonomy of soils in the Littlefield study area

Series	Family and higher
Bayboro	Clayey, mixed, thermic Umbric Paleaquults
Goldsboro	Fine loamy, siliceous, thermic Aquic Paleudults
Lynchburg	Fine loamy, siliceous, thermic Aeric Paleaquults
Norfolk	Fine loamy, siliceous, thermic Typic Paleudults*
Wagram	Loamy, siliceous, thermic Arenic Paleudults*
Troup	Coarse loamy, siliceous, thermic Grossarenic Paleudults*
–	Loamy, siliceous, thermic Arenic Paleaquults
–	Coarse loamy, siliceous, thermic Grossarenic Paleaquults

* These series have been formally reclassified as Kandiudults, but mapping units on the lower coastal plain rarely meet the kandic criteria (Kleiss, 1994)

granular A and E horizons overlying a series of mottled subangular blocky sandy clay loam argillic (Bt) horizons (Table I). The Norfolk and related soils are the single most common group of soils on uplands of the North Carolina coastal plain (Daniels *et al.*, 1984; Lee, 1955).

The taxonomy of soils mapped at the study area is given in Table II. Most of the soils can be interpreted relative to the Norfolk series (Figure 3). The Norfolk, Wigram and Troup series differ from each other only with respect to the thickness of the surficial A and E horizons (20 to 50, 50 to 100, and > 100 cm, respectively). This is reflected taxonomically in their placement in different textural families

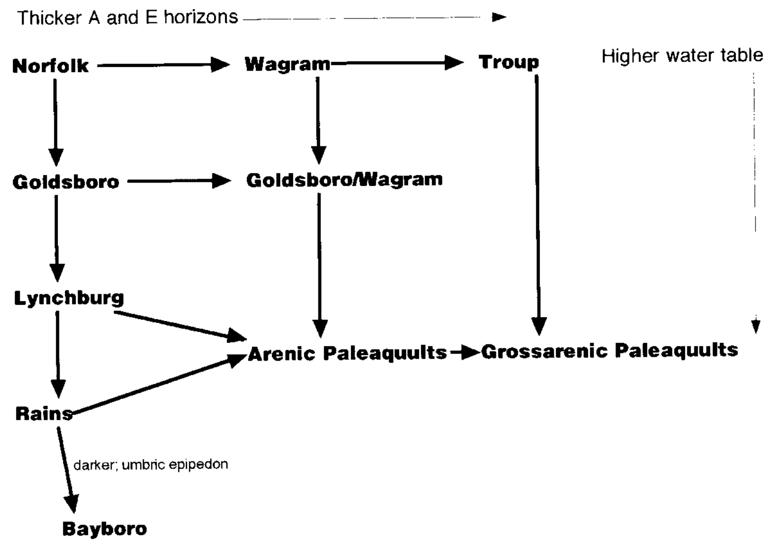

Figure 3. Relationships among the major soil types at Littlefield, based on the Norfolk series as a reference

and their assignment to typic, arenic and grossarenic subgroups. The Norfolk, Goldsboro, Lynchburg and Rains series are formed in similar parent material, and are the well, moderately well, somewhat poorly, and poorly drained members, respectively, of a drainage catena. They differ from each other only with respect to features related to drainage and water table depth. The poorly drained Bayboro series is formed from different parent material and is found on alluvial and marine terraces. As compared to the poorly drained Rains, it is darker, finer, and has an umbric epipedon.

Three soil types were mapped that do not correspond with recognized series. One to a soil that is similar to the Wagram (50 to 100cm depth to the top of the Bt horizons), but has a higher water table and is somewhat poorly drained. Alternatively, this soil could be intepreted as a thicker-surface, arenic version of the Goldsboro series. As this soil is found in a complex with Goldsboro and Wagram soils *per se*, the complex is referred to and mapped simply as Goldsboro/Wagram. Two other soils are generally similar to the Rains and Lynchburg series, but have much thicker A and E horizons. Conversely, these soils could be considered as somewhat poorly or poorly drained catenary relative of Wagram or Troup soils. For purposes of this study, these thick-surface, high-water-table Udults are referred to as Arenic or Grossarenic Paleaquults, according to whether the A and E thickness is 50 to 100 or >100cm.

Soil geography

The valley bottom is occupied by the Bayboro soils, which are restricted to the valley of the main stream/canal on the west side of the study area (Figure 4). Tributary drainage depressions now containing ditches are occupied by the Rains and Lynchburg series. The remainder of the study area will be referred to as uplands to distinguish it from the valley bottoms and drainageways.

The Norfolk soils are found on the upland cropped fields throughout the study area, but are especially prominent in fields E, B and A. This mapping unit includes some pedons of Wagram and Goldsboro soils. The Goldsboro soils are in slight depressions; the Wagrams are not correlated with any observed topographic or other surface features. Wagram soils or the Goldsboro/Wagram complex occupy much of the remainder of the upland croplands, the exception being a large area of Rains on a poorly drained upland flat on fields B and C. Wagram soils also occur on convex ridges within the forested area. The Goldsboro/Wagram unit is prevalent on the northernmost portions of the study area (Fields D, E and

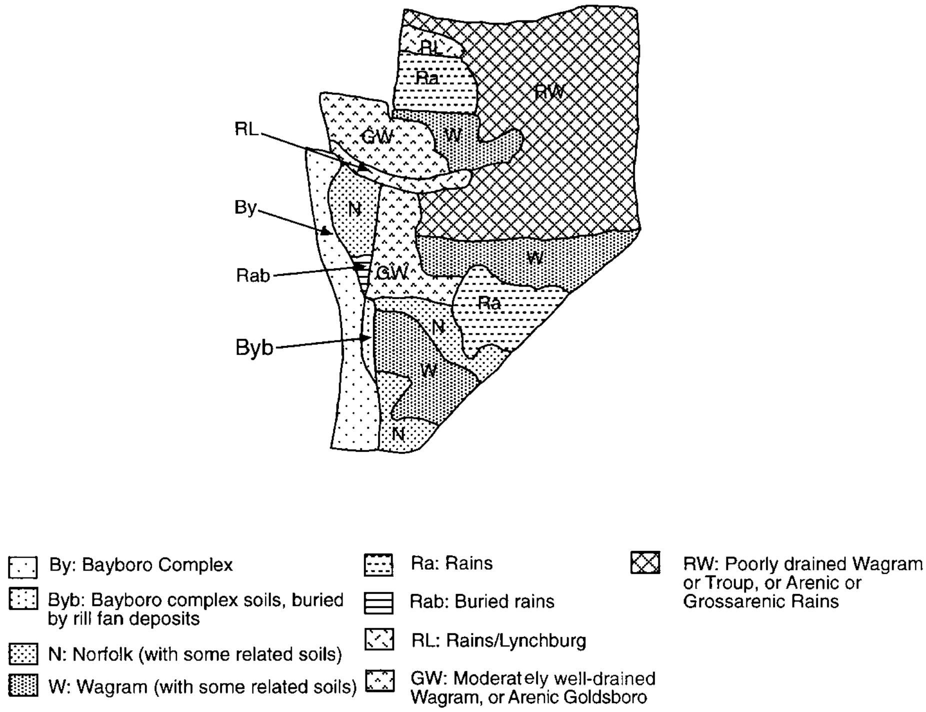

Figure 4. Soil map

C) and is absent from fields A and B. The Goldsboro, Wagram and hybrid soils in this complex occur with no observed relationship to topography or surface features.

In addition to occurring in a complex with Lynchburg in drainage depressions, the Rains series occupies two broad flat upland areas, one in the forest, and one in fields B and C. The Arenic and Grossarenic Paleaquults (the RW mapping unit) are confined to the woodland, and comprise the majority of the forested area. A few areas of Wagram and Troup soils, too small to map, occur on minor ridges in this mapping unit.

There are smaller areas of soils modified by surface processes. These will be discussed in more detail below, but include two areas of a buried Rains soil (fields B/C and E), and a strip of buried Bayboro along fields B and A. Other areas of secondary pedogenesis occur in a thin strip along the field–forest boundary.

Depositional soils

Three general types of soils modified by deposition are found: buried Rains and Bayboro soils, and soils associated with field-edge aeolian deposition. The latter are discussed separately. In the buried Rains soils, dark loamy sand and sandy loam horizons (Ab and Eb) are overlain by 20 to 35cm of lighter loamy sand. Both buried Rains delineations are in locations where there is limited local drainage area, but where tillage redistribution from nearby slope convexities may have resulted in net deposition in the topographic depressions occupied by the buried Rains.

The buried Bayboro soils are in toeslope areas of field B and the northwest portion of field A. During fieldwork in early 1997, rills were evident on the lower portions of field B, and extending downslope along the lower edges of fields B and A. The termini of these rill systems featured sandy fan deposits, many with ripple marks evident. The typical soil stratigraphy observed in February 1997, before

Table III. Dimensions of field-edge ridges

Site	Maximum elevation* (m)	Width (m)
FE1	0·34	23·5
FE2	0·20	8·5
FE3	0·25	10·0
FE4	0·53	11·0
FE5	0·52	10·0
FE6	0·40	3·5

* Relative to the immediately adjacent field

ploughing, was about 5cm of newly deposited light yellow sand, over about 20cm of dark loamy sand with lenses and discontinuous layers of light sand. From 25 to about 72cm is a dark loam, and from 72 to 125cm there are several layers of brown to black loamy sand and sandy loam. At about 125cm in the typical sequence is a grey sandy clay loam. The horizon sequence from 25 to $>$125cm is virtually identical to that found in the adjacent Bayboro soils. While there must be at least 50cm of burial to formally qualify for a buried horizon designation in the US Soil Taxonomic system (Soil Survey Division Staff, 1993), these sequences clearly represent material from the Norfolk and Wagram soils upslope deposited on the Bayboro soils at the slope base.

In general, the soils in the areas mapped as buried Bayboro had 0 to 19cm of newly deposited sand in February 1997, which was subsequently ploughed into the A horizon. The dark loamy sand cumulic A horizons extended to a depth ranging from 19 to 28cm, below which the typical Bayboro horizon sequence began. All the cumulic A horizons had lenses and mottles of light sand.

At the extreme lower edge of the toeslopes, grading to the railroad embankment or the Bayboro soils, no surface deposits from 1996/97 winter rill erosion were evident, the cumulic depositional A horizons were somewhat finer (sandy loam vs loamy sand), and mottling associated with iron-staining was evident.

Field edges

Along the forested field edges, small but obvious ridges are evident along the majority of the south- and west-facing edges. The ridges are generally 5 to 10m in width, and the crest elevations relative to the adjacent field and forest areas are 0·2 to 0·6m (Table III). The strict correspondence of these topographic features with the field–forest boundary suggests that they must be associated with land-use practices. Their height, width, and the minimal amounts of deposition observed during 1997 tillage operations suggest that these features are not attributable to tillage. Their upslope locations, and absence from the north-facing edge of field D and from the easternmost forested edges of field C, where fetch is limited, suggest that these are aeolian accumulations.

The ridges were trenched from the field edge to the ridge crest in two locations (Figure 5), and stratigraphy at the ridge crest was examined at eight additional locations. The trenches show that the depth to the top of the argillic horizon increases systematically towards the ridge crest. Near the crest, the A–E–Bt horizon sequence becomes more complex, with one or more podzolized B horizons evident. Typical horizonation of the ridge crests is summarized in Table IV. These in general show compound horizon sequences, with multiple E–B sequences, the uppermost characterized by Bh or Bw horizons associated with secondary podzolization.

There is some circumstantial botanical evidence of recent deposition at these sites, in the form of some buried basal flares on trees, and the appearance of multiple root layers. However, due to the mixed successional nature of the vegetation, the fact that the edge vegetation is periodically cut back, and the inability to get ring counts from buried basal roots, no dendrochronological evidence of deposition rates or timing was obtained.

The northeast portion of field D, exposed to southwesterly winds, showed evidence of aeolian

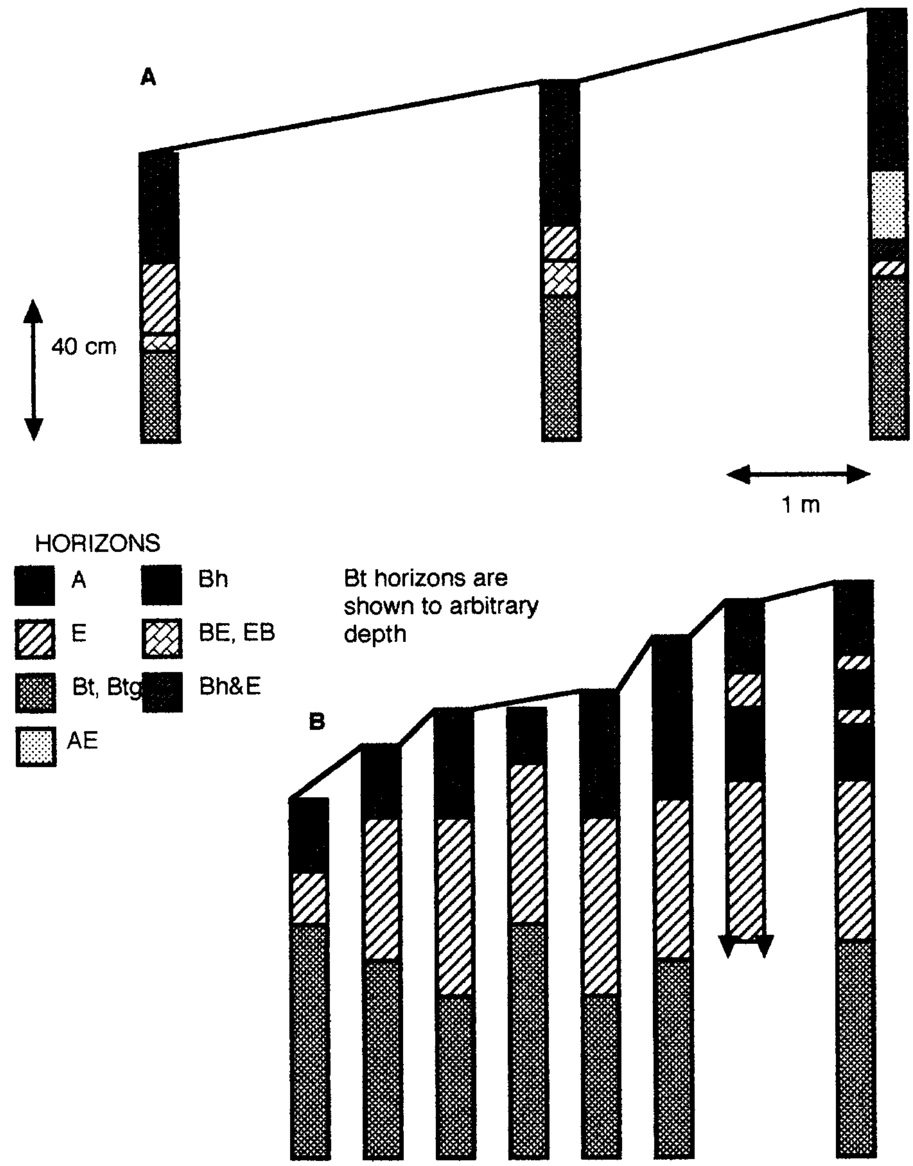

Figure 5. Soil stratigraphy at two trench sites along the field-edge ridges, from the field edge at the left of each sequence, to the ridge crest: (A) at FE6; (B) near FE1

deposition in the cultivated area in addition to the forest-edge ridges. A strip about 40m wide in this zone exhibited larger DTA values (51 to 147cm), and secondary pedogenesis. The horizon sequence in this area was A–E–Bw–Eb–Btb. The Bw horizons were generally yellow or brownish yellow, with hues of 10YR, values of 6 to 8, and chromas of 6 to 8. In a few pedons, dark Bh horizons were present instead of Bw horizons. The Bw or Bh horizons were generally 34 to 50cm below the surface.

A smaller ridge was evident along the south-facing ditchbank on field B. Here the loamy sand A and E horizons are 50 to 60cm thick. While the mean DTA in field B is about 52cm, in the portion of the field immediately adjacent to the ditch-edge ridge the DTA is much lower, generally 20 to 40cm. There was no evidence of secondary spodic development, but one of several buried shoots of the shrub *Smilax* spp. had adventitious root clusters 9, 16, 21, 29 and 39cm below the surface, indicating at least five separate deposition episodes.

Table IV. Soil stratigraphy of field-edge ridges

Site	Bh horizons	Bw horizons	Mixed horizons	Bt horizon	Horizon sequence
FE1	none	none	Bh & Bw & E 44, 19 Bh & Bw & Eg 63, 31	not found, >150	A–E–Bh & Bw & E– Bh & Bw & Eg–Egb
FE2	none	none	Bh & Bw 53, 18	Bt1 71 Bt2 127	A–E– Bh & Bw– Bt1–Bt2
FE3	none	Bw 51, 38	none	Bt 103	A–E–Bw–Eb–Btb
FE4	Bh 23, 38 Bh' 80, 13	none	none	not found, >123	A–Bh–Eg'–Bh'– Egb–Ab
FE5	Bh 23, 12	none	none	Bt 35 Btg 104	A–Bh–Bt–Btg
FE6	none	none	Bh & E 60, 6	Bt 72	A–AE–Bh & E– Eb–Btb
CE1	Bh 24, 11 Bh' 41, 12	none	none	Bt 100	A–E–Bh1–E'–Bh'– Eb–Btb
DE1	none	Bw 44, 60	none	Bt 145	A–E–Bw–Eb– EBb–Btb
DE2	none	Bw 44, 55	none	Bt 138	A–E–Bw–Eb–Btb

For Bh, Bw and mixed horizons the horizon designation is shown, followed by the depth to the top of the horizon, and the horizon thickness (in cm). Mixed horixons refer to those involving mixtures of Bh and/or Bw and/or E horizon material. For Bt horizons only the depth is given

DTA transects

The nine DTA transects indicated remarkable consistencies in mean surface horizon thickness between fields. The largest field, C, has a mean DTA of about 48cm, compared to 43, 52, 48 and 49cm, respectively, for fields A, B, D and E. Variations in extreme DTA values were considerable along most transects, typically ranging from thin surficial horizons (<25cm) where B horizon material was ploughed into the surface layer, to values >100 or even >150cm. However, with the exception of one transect (A1), standard deviations were not extreme, and were less than half of the mean value.

Attempts to relate within-transect variations in DTA to observed topographic or surface erosion/deposition features met with mixed success. This is summarized in Table V, which identifies the association between such features and the highest and lowest DTA values (thickest and thinnest surface horizons), and other DTA values more than one standard deviation greater or less than the mean. The most striking feature of Table V is that for more than half the table entries, high and low DTAs could not be related to observed erosion/deposition or land-use features, or to slope convexities or concavities, toeslopes or relatively steeper slopes. This is in contrast to other studies which have revealed systematic relationships between surface horizon thickness and observable erosion/deposition features and topography (King *et al.*, 1983; Gregorich and Anderson, 1985; Stone *et al.*, 1985; Lowrance *et al.*, 1988; Kreznor *et al.*, 1989; Mokma *et al.*, 1996).

Five transects in two fields (A and D) showed evidence of thicker soils associated with wind deposition, near forest boundaries (D) or along vegetated ditch borders facing in a generally southerly direction (A). Prevailing winds, particularly during drier periods, are from the southwest. Two transects (D2, E1) showed evidence of thinner soils on convexities, generally associated with a net loss from tillage redistribution and with aeolian erosion, and one other (A2) had thickest soils downslope of a convexity, a pattern consistent with tillage redistribution (Govers *et al.*, 1994; Quine *et al.*, 1994; Vandaele *et al.*, 1996; Poesen *et al.*, 1997). Conversely, one transect (A2) had the thickest surficial horizon on a convex slope. Field B showed some evidence of fluvial processes, with highest DTAs at a toeslope (buried

Table V. Association of highest and lowest depth-to-argillic (DTA) horizon measurements with topographic, geomorphic or pedologic features

Transect	Highest DTA*	Other high*	Lowest DTA*	Other low*
A1	S-facing ditch bank	None†	Unknown	None
A2	Convex slope	S-facing ditch bank	Unknown	Unknown
A3	Downslope of convexity	S-facing ditch bank	Unknown	Unknown
B1	Rill fans, buried Rains	Unknown	Unknown	Slope break area‡
C1	Unknown	Flat upland, slope base	Unknown	Flat upland
C2	Unknown; Bt missing?	Concave slope base; unknown	Unknown	Unknown
D1	Field-edge ridge	Aeolian deposition zone	Unknown	Unknown
D2	Field-edge ridge	Aeolian deposition zone	Unknown	Convex slope
E1	Buried Rains	Unknown	Convex slope	Unknown

'Unknown' indicates no association with observed features.
* Highest and lowest DTA values are the maximum and minimum single measurements. Other high and low values refer to measurements more than one standard deviation different from the transect mean.
† All but highest and lowest values very close to transect mean
‡ Where relatively flat upper field begins sloping downward

Bayboro soils) and lower DTA values in the zone where the flat upper (eastern) portion of the field begins sloping more steeply towards the lower, rill-dissected end. In general, though, DTA patterns on transect B1 are difficult to interpret, as are many of the other patterns (Table V).

DTA values in areas of the forest mapped as RW (Arenic and Grossarenic Palaequults) and Wagram ranged from 52 to >150cm, the latter value being the practical limit of sampling in the wet soils. If the >150 sites are treated as DTA = 150cm for averaging purposes, the mean DTA in these areas is 116cm. The median DTA is 130cm.

Cemetery

The topography of the cemetery itself is irregular, and the field as a whole slopes away towards the north and east portions of the plot. Thus the elevation difference between the cemetery and the field ranges from about 20 to 90cm, with a mean of 55cm. There is no evidence that the graveyard occupies a pre-existing topographic high; therefore the elevation difference must be attributable to surface lowering in the cultivated area and/or accretion or expansion on the cemetery surface.

We were able to obtain eight reliable DTA measurements on apparently undisturbed surfaces within the cemetery, though the highest portions of the plot were those occupied by graves and could not be sampled. The mean was 68·25cm. This compares to the mean DTA for the field as a whole of 48cm. At the soil pit 17m away, 23DTA measurements around the boundaries of the pit at 20cm intervals gave a mean of 36·9cm and a range of 29 to 48cm. Four of the cemetery DTA measurements were at the corners; in these cases two DTA measurements were made in the cultivated soils immediately adjacent. The latter comparisons suggest truncation of 14 to 66cm, with a mean of 32·75cm. Taken together, these results imply 20 to 33cm of truncation.

Six samples each of cemetery and field A horizons yielded mean bulk densities of 1·12 and 1·6g cm^{-3}, respectively. This suggests that about 25 per cent of the truncation is due to compaction.

Some headstones appeared to be partially buried at the bases, and microscopic examination of surface soil samples indicates an enrichment of silt compared to the field soils. This indicates some trapping of aeolian sediment, but this is believed to be minor, based on the lack of pervasive evidence of burial of headstones and vegetation on the cemetery surface. There is one large tree and numerous shrubs on the plot, and expansion associated with their root systems is probably also a minor contributor to the elevation of the surface.

Accordingly, we estimate that only about half the elevation difference is due to surface lowering (erosion and compaction) of the surrounding cropland, and most of the remainder is due to the volumetric expansion and mass additions associated with interment.

The oldest identifiable headstone was emplaced in 1909, but several older stones were unreadable. Given this minimum cemetery age of 88 years at the time of measurements, the maximum truncation of 33 cm (24·75 cm attributable to erosion), and a bulk density of 1·6 g cm^{-3}, we may estimate a *maximum* historic erosion rate of 45 t ha^{-1} a^{-1}. This is no doubt an overestimate of all but the most severely eroded portions of the site, but provides an upper constraint on estimated rates at the Littlefield site.

DISCUSSION AND INTERPRETATION

The tenuous relationship between DTA values and surface features suggests two general possibilities. The first is that factors other than surficial soil redistribution have important influences on surface horizon thickness, i.e. that there is intrinsic variability in A and E horizon thickness independent of truncation and accretion. The second is that water, wind and tillage redistribution are all significant on many of the fields and partially obscure each other's effects. These processes have different relationships with topography (DeJong *et al.*, 1986; Pennock and DeJong, 1990; Sutherland and DeJong, 1990; Govers *et al.*, 1994; Quine *et al.*, 1994; Vandaele *et al.*, 1996). For example, tillage processes result in maximum net soil loss on convexities, and deposition in concavities, while fluvial erosion generally leads to erosion of concave slopes. Fluvial processes are closely associated with slope steepness, shape and drainage contributing area, while aeolian processes are controlled by exposure to winds and soil moisture. The simultaneous or contemporaneous operation of two or three of these mechanisms could obscure soil thickness evidence of their effects; for example, when fluvial erosion of relatively steep convave slopes is partially obscured by tillage deposition in the same area.

It is likely that both intrinsic spatial variability and multiple redistribution processes are contributing to the observed patterns. Daniels (1987) has criticized the use of soil profile truncation to estimate soil loss, due to the variability of horizon thicknesses in undisturbed soils. Significant, and often dramatic, spatial variability in surface horizon thickness and other gross morphologic properties over length scales of tens of metres, even with no observable variation in soil-forming factors, has been documented in several settings in the North Carolina coastal plain (Phillips *et al.*, 1994, 1996). However, the other soil stratigraphic evidence makes it evident that soil redistribution is occurring at Littlefield.

The location, size and morphology of the field-edge ridges indicates an aeolian source for these features. Observations during the 1997 field season (and aeolian process measurements to be reported separately) confirm that wind erosion is an important process at Littlefield. Further, reconnaissance in other agricultural areas of eastern North Carolina suggests that ridges or berms at downwind field boundaries are ubiquitous, and fresh aeolian accumulations were evident in many locations during the late winter/early spring 1997 'wind season'. The secondary pedogenic features (Bh, and Bw horizons that appear to be incipient Bs horizons) are consistent with the podzolization that typically occurs in dune sands in humid subtropical climates, including those in eastern North Carolina (Thompson, 1983; Phillips *et al.*, 1996). A smaller ditch ridge on field B lacks secondary pedogenic features but appears to be due to aeolian deposition, as do the thicker soils on the north side of the field A. Some soils on the north and west sides of field D also have secondary pedogenic features in what appear to be surface aeolian deposits.

Fluvial erosion and transport is also clearly occurring at Littlefield, as deposition in drainage ditches and canals, and suspended sediment concentrations of 200 to 300 mg l^{-1} during winter 1997 storm flows attest. Fluvial processes are clearly responsible for substantial redistribution in fields A and B, where rill erosion and deposition were observed, and where the depositional signature of rill fan deposits is clear in the cumulic horizons of the buried Bayboro soils.

Tillage redistribution may be responsible for the thin soils on the convexities in field E, where profile truncation has resulted in the mixing of yellowish brown B-horizon material in the plough layer, giving

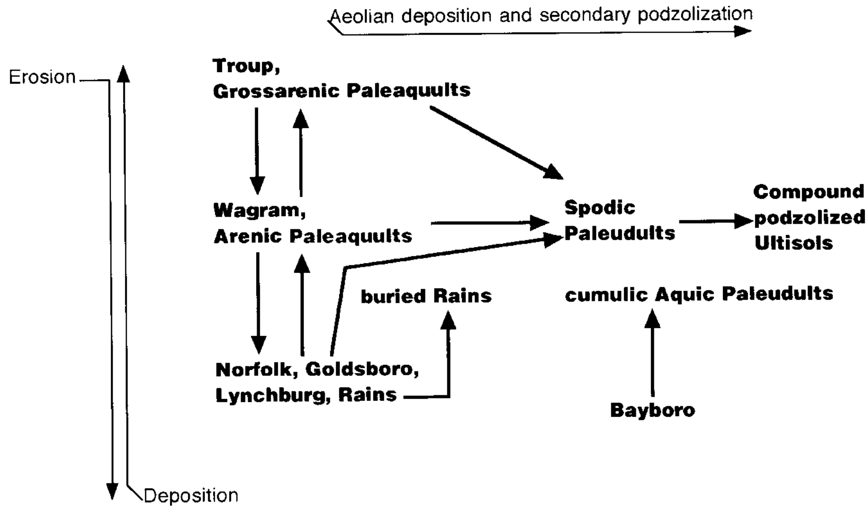

Figure 6. Soil transformations at Littlefield. Observed changes are indicated by the arrows connecting soil types. The direction and nature of the changes are indicated by erosion and deposition (vertical axis) and aeolian deposition with secondary podzolization (horizontal axis). The erosion–deposition axis does not necessarily imply reversibility at a specific location, but rather that the transformations may occur in either direction at different locations within the field system

these sites a distinctive colour contrast. Aeolian soil loss could also play a role. Tillage does appear responsible for the buried Rains soils, neither of which is situated such that fluvial or aeolian deposition is likely. It appears that repeated cultivation is leading to a net accumulation in these slight depressions.

Soil transformations

To the soils identified in Table I and Figure 3, we may add four additional soil types. These are the buried Rains, buried Bayboro, and two associated with aeolian deposition which we refer to as Spodic Paleudults and compound podzolized Ultisols. Spodic Paleudults are characterized by spodic development, such as humic or iron oxide concretions, or Bw horizons interpreted to be incipient Bh, Bs or Bhs layers, within or mixed with the A and E horizons. Some of these soils would be classified as the Onslow series, which is mapped in eastern North Carolina and has an E/Bh horizon characterized by cemented nodules. Compound podzolized Ultisols are those where secondary pedogenesis has created full E–B horizon sequences within the deposited materials. The term 'compound' is chosen because in US Soil Taxonomy, the term 'bisequal' implies that the sequa formed contemporaneously, which is not the case here. Some, but not all, of these compound soils would meet the 50cm criterion for buried soils.

The soil transformations are depicted graphically in Figure 6. In general, they involve the effects of erosion and truncation, deposition and associated upbuilding and burial, and secondary pedogenesis. The transformations are described in more detail below.

The differences between the Troup/Grossarenic Paleaquults, Wagram/Arenic Paleaquults, and Norfolk catena soils are defined by the thickness of the A and E horizons or depth of the argillic horizons. Thus, because truncation and accretion on the order of tens of centimetres has occurred, transformations between these groups of soils has apparently transformed the soil map at Littlefield, and no doubt will continue to do so, at least at local (within-field) spatial scales. At a broader scale, erosion and compaction associated with cultivation have apparently transformed the thicker-surface soil types found only in the forest (Troup, Grossarenic and Arenic Paleaquults) into the thinner Goldsboro/Wagram, Norfolk and Rains soils found in the cultivated fields.

The transformations above, which result in shifting among soil types already present at the site, can be contrasted with those resulting in the creation of new soils. Deposition, due primarily to fluvial

processes, has transformed Bayboro soils into the cumulic Aquic Paleudults mapped as buried Bayboro. Deposition, apparently due mainly to tillage, has transformed the poorly drained Rains into the somewhat poorly or moderately well drained variants mapped as buried Rains. Aeolian deposition of dominantly quartz sand, and subsequent secondary podzolization result in the transformation of the Paleudults and Paleaquults into Spodic Paleudults and compound podzolized Ultisols.

The mapped areas of buried Rains and Bayboro soils are 0·35 and 0·95ha, respectively. An estimated 0·64ha of the area mapped as Wagram in field D consists of Spodic Paleudults in strips near the field edge. This area, too small to map on Figure 5, is in the field adjacent to the field-edge ridges. The field-edge ridges have a mean width of 11·5m along the 410m of south-facing forest boundary and a mean width of 8m along the 320m of west-facing boundary. This amounts to an additional 0·73ha of Spodic Paleudults and Podzolized Ultisols. Thus, about 2·67ha or 7·6 per cent of the cultivated portion of the study area consists of new soils produced by redistribution of surface materials.

It is impossible to say precisely how much of the surface area has undergone transitions among the Grossarenic, Arenic, and Typic Paleudults and Paleaquults. Eroding areas have apparently undergone about 15 to 33cm of lowering due to erosion and compaction. In this sense, about half the study area (the 35 cultivated hectares) has undergone a transition. The truncation estimate is based on the cemetery data, but is less than the general DTA differences between the forested and cultivated areas, and is consistent with previous studies of profile truncation in the southeastern coastal plain (Cooper *et al.*, 1987; Lowrance *et al.*, 1988; Phillips, 1993, 1997; Phillips *et al.*, 1993). Our guess is that about 20 per cent of the cultivated area has experienced truncation or accretion sufficient to result in taxonomic reclassification, independently of or in addition to the general transition from the thicker forested to the thinner cultivated soils.

The Littlefield area is not atypical of eastern North Carolina agricultural landscapes. The features we examined, such as field-edge ridges, the elevated cemetery and toeslope rill fans, are common in the region. Thus, soils similar to the transformed soils observed at Littlefield are likely to be common. If this is true, the widespread importance of colluvial storage and a mix of water, wind and tillage redistribution processes in the region will be confirmed. Future work of this nature, combined with contemporary process measurements and/or dating of soil features, should lead to progress in direct quantitative estimates of the quantities and rates of colluviation and soil redistribution.

CONCLUSIONS

At Littlefield, soil redistribution associated with cultivation has resulted in five general types of soil transformation, which reflect upland soil redistribution processes at the site. First, erosion and compaction in the cultivated area have resulted in the thinning of Arenic and Grossarenic Paleudults and Paleaquults, with typical A- and E-horizon thickness of >100cm, to form Arenic, Typic, and Aquic Paleudults and Paleaquults, with typical surficial horizon thickness of 42 to 52cm. Second, redistribution of surficial material within the fields results in transitions between Arenic and Typic/Aquic subgroups, as loamy sand A and E horizons are truncated or accreted. Third, aeolian deposition at forested field boundaries forms soils with spodic features in the A and E horizons or secondary podzolized profiles over buried soils. Fourth, sandy rill fan deposits at slope bases create cumulic soils distinct from the loamy sands of the source area or the darker, finer terrace soils buried by the fan deposits. Finally, tillage and fluvial deposition in upland depressions result in the gradual burial of Rains (poorly drained Typic Paleaquults) soils.

There are five general types of direct soil change associated with erosion and deposition, as discussed in the Introduction: truncation, horizon destruction, upbuilding, burial, and secondary pedogenesis. Though horizon destruction is confined to the loss of O horizons when forests are converted to agriculture, all are observed at Littlefield. The evidence of soil redistribution reflected in soil stratigraphy and morphology can be useful in getting a better picture of soil redistribution processes and sediment storage. In this case it suggests that soil removal and redistribution due to tillage and wind processes, as

well as extensive colluvial storage, accounts for the large disparity between upland soil loss and sediment delivered to streams.

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